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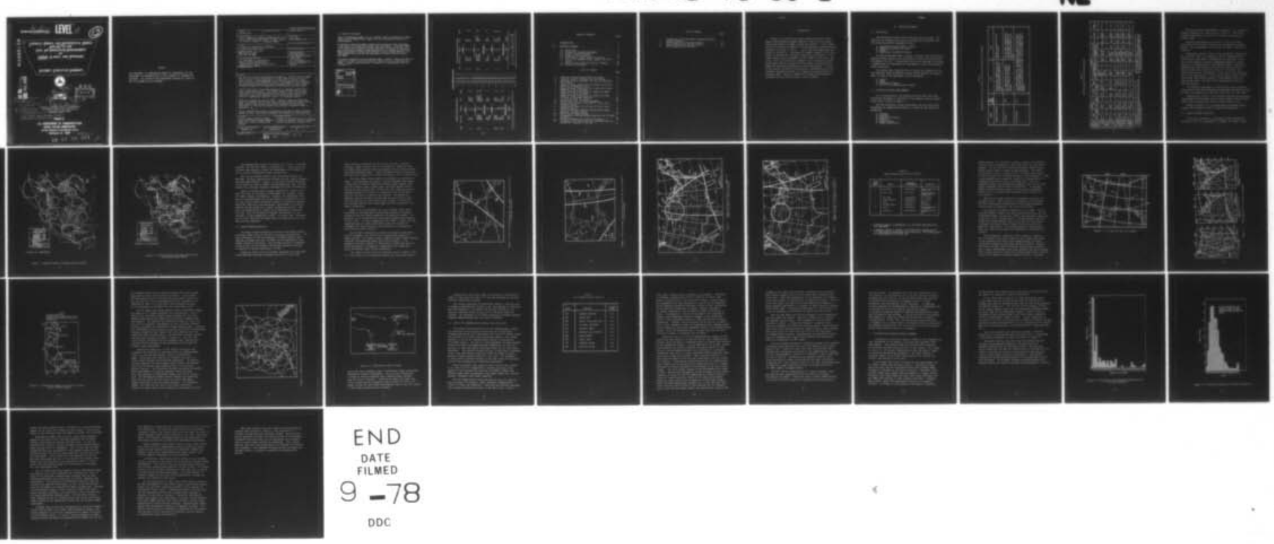

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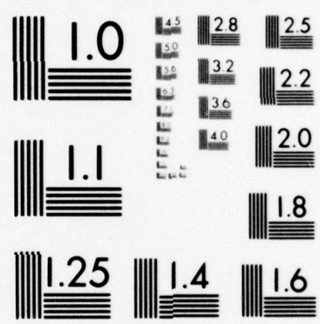

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REPORT NO. FAA/RD-78-30-I **LEVEL** III

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LORAN-C, OMEGA, AND DIFFERENTIAL OMEGA APPLIED TO THE CIVIL AIR NAVIGATION REQUIREMENT OF CONUS, ALASKA, AND OFFSHORE.

VOLUME I. EXECUTIVE SUMMARY.

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F. G. Farkalik
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16. Abstract

The objectives of this study were basically twofold. The first was to validate the civil air navigation requirements for CONUS, CONUS Offshore, Alaska, and Alaska Offshore. A requirements matrix was developed to provide a common basis for defining the requirements across all the geographic areas considered. The second basic objective was to assess the capabilities of Loran-C, Omega, Differential Omega, and VLF communications toward meeting the requirements.

Loran-C offers total all-altitude coverage for all geographic regions given existing and proposed chains. The primary drawback is the large area and, hence, number of aircraft affected by single station outage. With suitable redundancy, Loran-C could meet the civil air navigation requirements as a primary or supplementary navigation system in all geographic regions.

Omega lacks adequate coverage over CONUS. Therefore, Omega and Differential Omega are candidates only in Alaska, Alaska Offshore and most of CONUS Offshore. Omega, however, does not meet the accuracy requirements for nonprecision approaches or in high density terminal areas, whereas, Differential Omega is expected to.

The VLF communications system is not dedicated to navigation, hence, reliability becomes an issue. With suitable redundancy the scheduled and unscheduled down

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16. Abstract (Continued)

times for maintenance becomes less of a problem. Used in conjunction with Omega signals, the VLF communications signals will provide adequate redundancy and usable geometry.

A potentially significant benefit offered by the candidate systems considered is the support of non-precision approach (NPA) requirements. A separate element of the study, which analyzed all systems considered, was devoted to this topic. Loran-C was found to exceed the NPA requirements in all regions and Differential Omega exceeded them in Alaska, Alaska Offshore and most of CONUS Offshore. The other systems did not meet the NPA requirements including Differential Omega over CONUS.

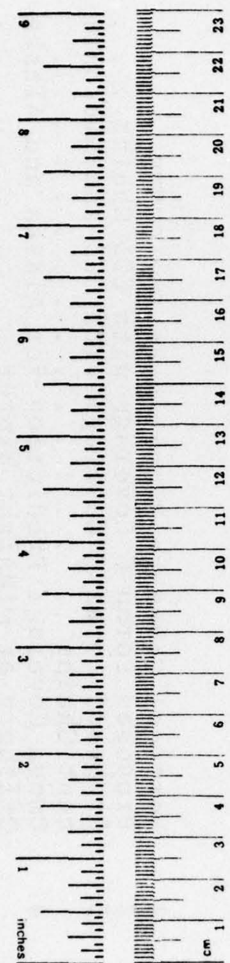
The report is presented in three separate volumes. Volume I presents the executive summary and Volume II presents the detailed technical analysis supporting this summary. Further supportive material is presented in the appendices which make up Volume III.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

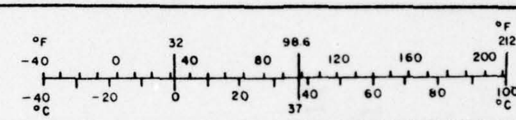
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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I. INTRODUCTION

Volume I is the first of three volumes entitled, "Loran-C, Omega, and Differential Omega Applied to the Civil Air Navigation Requirements of CONUS, Alaska and Offshore." This volume presents an executive summary of the navigation system evaluation presented in Volume II and supported by detailed appendices presented in Volume III. The executive summary appears in the same format as the detailed technical discussion of Volume II. The format begins with a statement of the primary objectives of the study. This is followed by a summary of the navigation system requirements and an evaluation of the degree to which Loran-C, Omega and Differential Omega meet these requirements. A significant benefit potentially realizable by implementation of the candidate navigation system is in support of non-precision approaches (NPA). Hence, a summary of a detailed NPA analysis performed as part of this study is also included.

II. EXECUTIVE SUMMARY

2.1 OBJECTIVES

The objectives of this study were basically two fold. The first was to validate the civil air navigation requirements for the following specific geographic areas:

- Continental United States (CONUS)
- CONUS Low Altitude Off-shore
- Alaska
- Alaska Low Altitude Off-shore

In each requirement area, enroute, terminal, and non-precision approach flight regimes were considered for both IFR and VFR with the emphasis on IFR. A requirement matrix was developed to provide a common basis for defining the requirements across all geographic areas considered.

The second basic objective was to assess the capabilities of the following radio navigation systems toward meeting the requirements in each of the geographic areas considered:

- Loran-C
- Omega
- Differential Omega
- Use of VLF Communications Signals

2.2 NAVIGATION SYSTEM REQUIREMENTS

As a starting point, the minimum aircraft radio and radio navigation equipment as specified by the Federal Aircraft Regulations (FAR) is shown in Table 1.

The IFR navigation system requirements for the three areas considered are summarized in Table 2 in terms of the following parameters:

- Coverage
- Accuracy
- Operational Factors
- Capacity
- Compatibility
- Signal Reliability

Table 1

Minimum User Aircraft Radio and Radio Navigational Equipment

USER	FAR PART NUMBER	IFR	VFR
General Aviation	91	Two-way radio communications and navigation equipment appropriate to the ground facilities to be used.	Compass, airspeed indicator, and altimeter.
Air Taxi	135	One communications transmitter, two receivers for navigation and two receivers for communications.	Two-way radio communications and navigation equipment to receive radio signals from the ground facilities to be used.
Air Carrier	121	One communications radio, two independent receivers for meteorological information, two independent systems to receive radio navigational signals from all primary enroute and approach navigational systems intended to be used; only one landing system is required.	

Table 2

IFR Navigation System Requirements

USER	FLIGHT PHASE	REGION	COVERAGE						ACCURACY (2D)	OPERATIONAL								CAPACITY	COMPATIBILITY	SIGNAL RELIABILITY
			CONUS		ALASKA		OFF-SHORE													
			VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL		FLEXIBILITY	POSITION PRESENTATION	COMMON INPUT FORMAT	PILOT WORKLOAD	FAILURE ALERTS	POSITION RESOLUTION AMBIGUITY	TIME TO REACQUIRE				
IFR	ENROUTE	NON-MOUNTAINOUS	2000 AGL TO FL 600	TOTAL	2000 AGL TO FL 600	TOTAL	500 AGL TO 10,000 MSL	200 NMI OFF-SHORE	± 4 NMI 95%	YES (5)	COURSE DEVIATION, NMI (6) ρ/θ LAT/LON	YES	(7)	MUST BE AVAILABLE	LESS THAN 0.5% OF THE TIME	1-2 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
IFR	ENROUTE	MOUNTAINOUS	2000 AGL TO FL 600	(1)	2000 AGL TO FL 600	TOTAL	NOT APPLICABLE	NOT APPLICABLE	± 4 NMI 95%	YES	COURSE DEVIATION	YES	(7)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.5-1 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
IFR	TERMINAL	HIGH DENSITY	200 AGL TO 14,500 MSL	(2)	200 AGL TO 14,500 MSL	(2)	200 AGL TO 10,000 MSL	(2)	(4,9) ± 2 NMI 95%	YES	COURSE DEVIATION	YES	(8)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.25-0.5 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
IFR	TERMINAL	LOW DENSITY	200 AGL TO 14,500 MSL	(2)	200 AGL TO 14,500 MSL	(2)	200 AGL TO 10,000 MSL	(2)	(9) ± 4 NMI 95%	YES	COURSE DEVIATION	YES	(8)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.5-1 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
IFR	NON-PRECISION APPROACH		250 AGL TO 14,500 MSL	(3)	250 AGL TO 14,500 MSL	(3)	250 AGL TO 10,000 MSL	(3)	± 1.5 NMI	YES	COURSE DEVIATION	YES	(8)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.25 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT

(1) Equivalent to current and increasing with time to reflect projected traffic density increases.
(2) All terminal areas being servied currently and those projected to be serviced.
(3) All airports currently with non-precision approach procedures and those where such procedures are expected to be required.
(4) 3D - ± 2.0 NMI, 4D - $\pm .15$ NMI
(5) Not a hard requirement, but does have significant cost impact.
(6) Enroute preplanned direct only.
(7) Less than or equal to single waypoint VORTAC-based RNAV system.
(8) Less than or equal to dual waypoint VORTAC-based RNAV system.
(9) ± 2 NMI in terminal maneuvering area (within 15 NMI of airport) ± 4 NMI beyond 15 NMI from the airport.

Vertical coverage requirements are based on the controlled airspace boundaries as illustrated in Figure 1. Horizontal coverage requirements are based on current and projected air traffic needs.

Accuracy requirements are related to the route width associated with the route structure in the National Airspace System. The requirements are the same for CONUS, Alaska, and Offshore.

Operational factors relate to the navigation system interface with the other ATC components, namely, communications, surveillance, and safety. Flexibility, as used here, has to do with the ability to easily accommodate changes in route structure, including course, altitude and fixes or waypoints. Reacquisition time relates to the time to activate the navigation system from an inactive state or to reacquire the system following an interruption. This time is also representative of an upper bound for position fix update rates in that the maximum time between updates is represented by the reacquisition times. The rest of the operational factors are self explanatory.

The capacity requirement is specified as being unlimited, which implies that the navigation system under consideration must be able to accommodate all aircraft accessing it at any time.

Compatibility refers to the interface between the navigation system under consideration and all other systems within the ATC system from an operational and electrical point of view.

Signal reliability is a specification of maximum signal outage time acceptable based on safety considerations.

2.3 LORAN-C SYSTEM EVALUATION

Loran-C was assessed as a potential primary navigation system, as well as a supplement to VOR/DME, for CONUS, Alaska

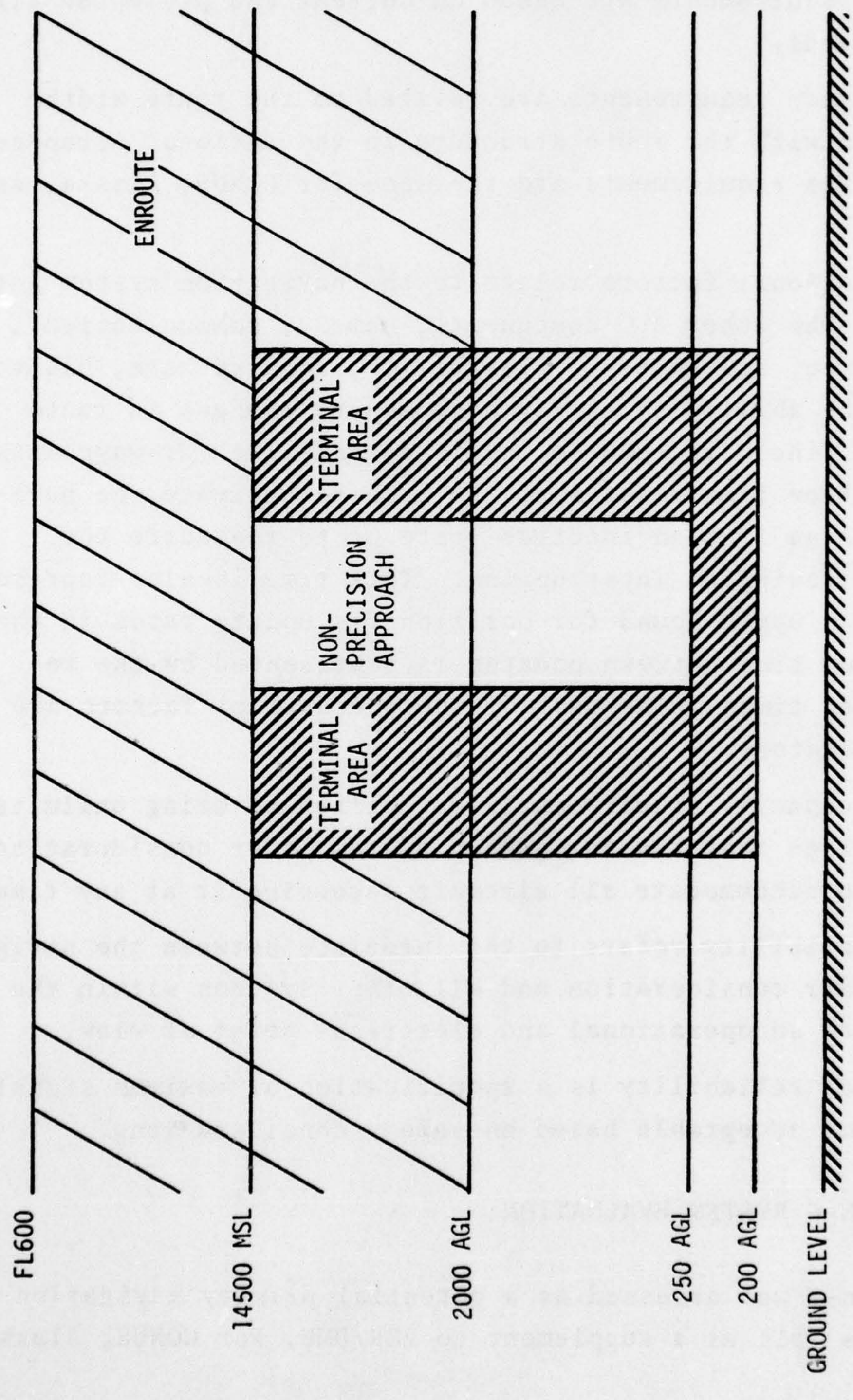
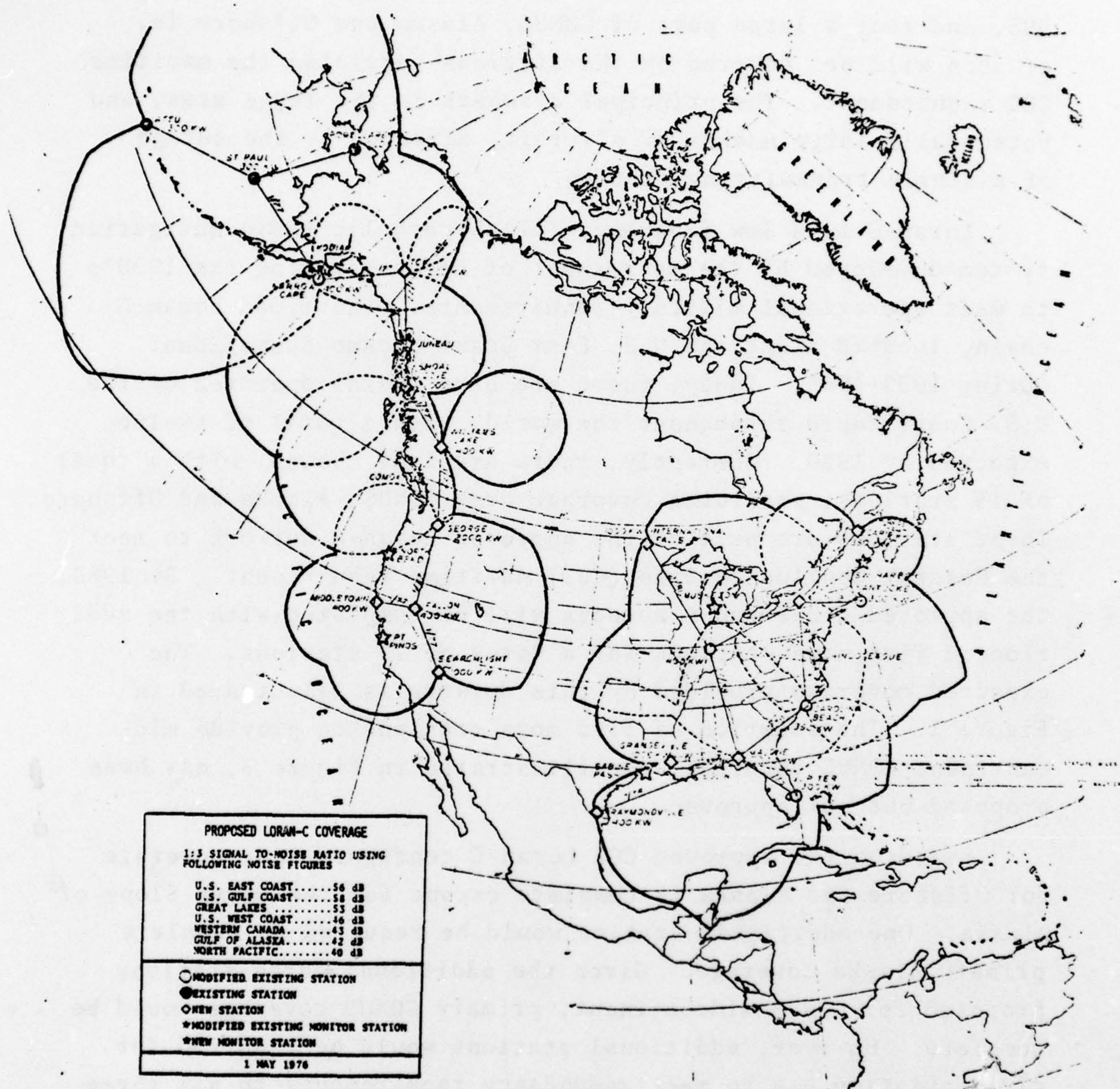


Figure 1 Vertical Coverage Requirement for CONUS

and Offshore. The primary advantage offered by Loran-C is total, all-altitude coverage which is not possible with VOR/DME, and that a large part of CONUS, Alaska and Offshore is, or soon will be, covered by the stations servicing the maritime CCZ requirement. The principal drawback is the large area, and potentially large number of aircraft, affected by the outage of a single transmitting station.

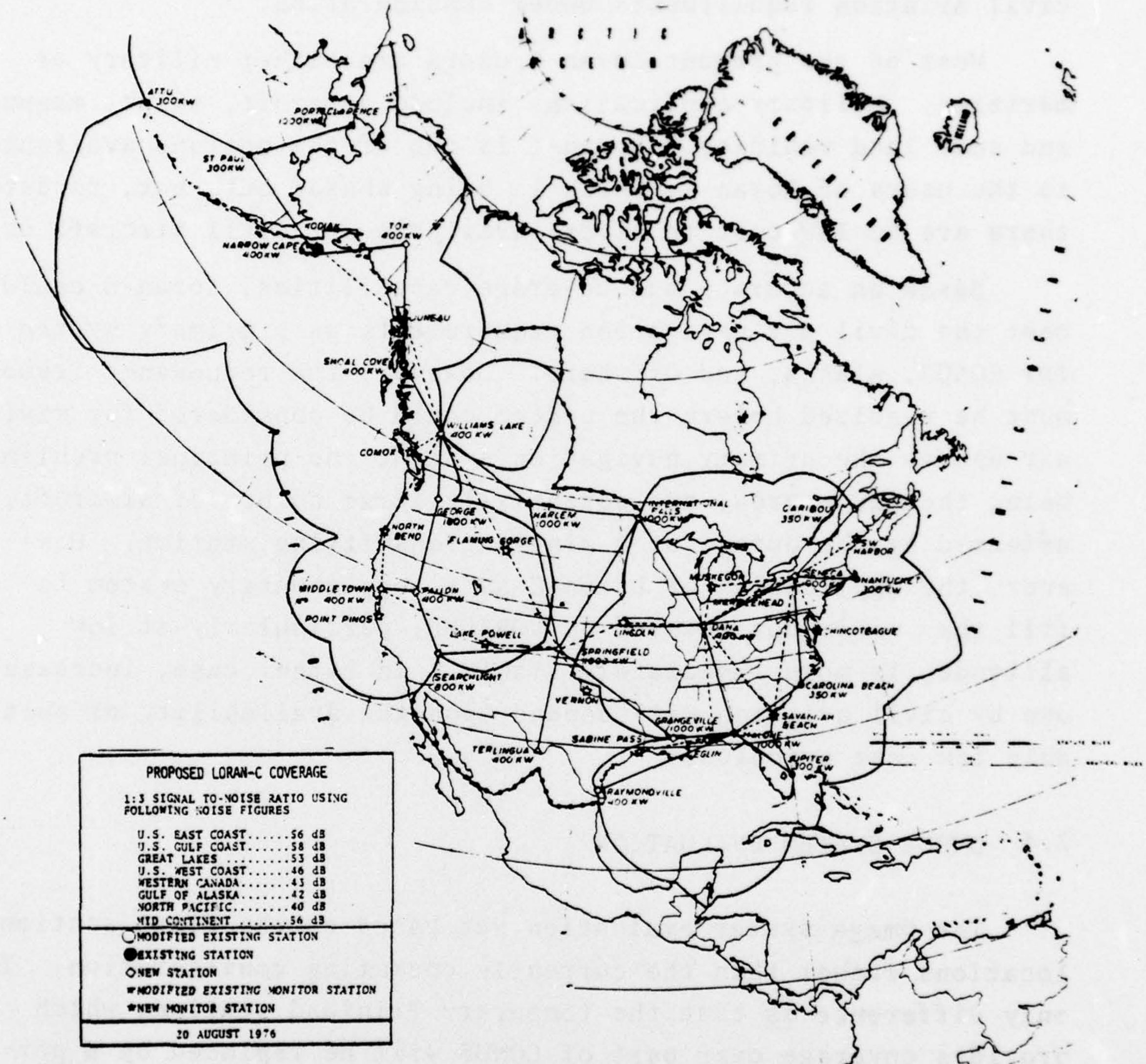
Loran-C is a low frequency (LF) hyperbolic radio navigation system developed by the Department of Defense during the 1950's to meet operational military requirements. The first Loran-C chain, located along the U.S. East Coast became operational during 1959-1960. Today, there are nine chains operated by the U.S. Coast Guard throughout the world, with a total of twelve expected by 1980. Currently, there are four chains, with a total of 15 stations, providing coverage over CONUS, Alaska and Offshore. These stations are part of the approved Loran-C network to meet the Coastal Confluence Zone (CCZ) maritime requirement. By 1980, the approved CCZ Loran-C network will be completed with the addition of five more stations for a total of 20 stations. The expected coverage provided by this network is illustrated in Figure 2. The addition of five more stations to provide mid-continent CONUS coverage, as illustrated in Figure 3, has been proposed but not approved.

Based on the approved CCZ Loran-C configuration, coverage for Offshore and Alaska is complete except for the North Slope of Alaska. One additional station would be required to complete primary Alaska coverage. Given the additional three stations proposed for CONUS midcontinent, primary CONUS coverage would be complete. However, additional stations would be required for civil aviation use to meet redundancy requirements in all three areas. Estimates to meet the redundancy requirements for all three areas range from 19 to 23 more stations.



(source: U.S. Coast Guard)

Figure 2 Proposed Loran-C Coverage with CCZ Chains



(Source: U.S. Coast Guard)

Figure 3 Proposed Loran-C Coverage with the CCZ and Midcontinent Chains

The demonstrated accuracy of Loran-C is 0.25 to 1.0 nm (RMS) absolute, and 300 feet (RMS) in repeatability. These accuracies are more than adequate to meet the requirement of all phases of civil aviation requirements under consideration.

Most of the present Loran-C users are either military or maritime. Military applications include aircraft, ships, manpacks, and some land vehicles. Loran-C is one of the options available to the users of Loran-A, which is being phased out, but, to date, there are no low-cost receivers available for civil aircraft use.

Based on accuracy and coverage capabilities, Loran-C could meet the civil air navigation requirements as a primary system for CONUS, Alaska, and Offshore. However, the redundancy issue must be resolved before the system could be considered for civil air use as the primary navigation system, the principal problem being the large area, and potentially large number of aircraft, affected by the outage of a single transmitting station. However, the application of Loran-C as a supplementary system to fill the voids not covered by VOR/DME, particularly at low altitude, is more immediately viable. In either case, increased use by civil aviation will depend upon the availability of suitable low-cost avionics.

2.4 OMEGA SYSTEM EVALUATION

The Omega system evaluation was based on the final station locations rather than the currently operating configuration. The only difference is that the temporary Trinidad station, which provides coverage over part of CONUS will be replaced by a permanent station in Australia. The Trinidad station is scheduled to go off the air on 31 March 1978 and the Australian station is expected to become operational in 1980.

Omega was found to be an excellent candidate for Alaska and Alaska Offshore with good coverage from four to six of the

eight stations, depending on time of year and day. Based on coverage, signal-to-noise ratios, and geometry, Omega can meet the enroute and terminal area requirements over the entire Alaska and Alaska Offshore region. Predicted Omega station coverage for best and worst conditions is shown in Figures 4 and 5, respectively.

The final Omega system cannot be considered a candidate for CONUS. As illustrated in Figure 6, during midsummer and midday, a large part of central CONUS will receive usable signals from only two stations with a region about the North Dakota station limited to only one station. Recent test data indicate that the coverage boundary for station F, (Argentina) may not actually reach as far north as shown on this figure. This means the Offshore area in the Gulf of Mexico may not be covered by more than two stations for much of the time. Figure 7 illustrates the coverage expected over CONUS under the best conditions; midnight at midwinter.

Omega is an international very low frequency (VLF) radio navigation system dedicated to providing a global all weather navigation and positioning capability of moderate accuracy. It operates in the internationally allocated frequency band between 10 and 14 kHz. At these frequencies, the earth's surface and the ionosphere act as a wave guide which allows the signals to propagate over long distances with relatively low attenuation and relatively high stability.

The system is designed to provide all weather navigational service throughout the world with a transmitting complex of eight stations. The eight stations along with their identification, location, and operating agency are listed in Table 3. The permanent stations transmit at 10KW which is sufficient power at these frequencies to propagate a signal half way around the world and farther under certain conditions.

The Omega Navigation System Operations Detail (ONSOD) of the U.S. Coast Guard is the responsible agency for the United States.

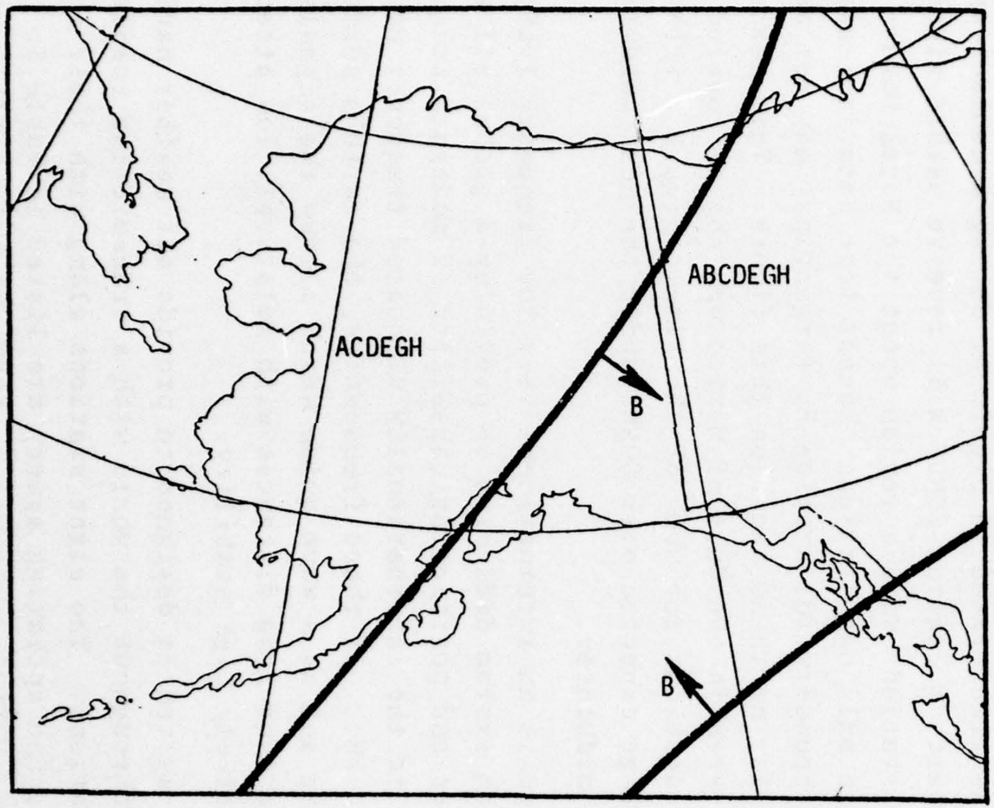


Figure 4 Omega Coverage Prediction for Alaska and Alaska Offshore at Midnight Midwinter

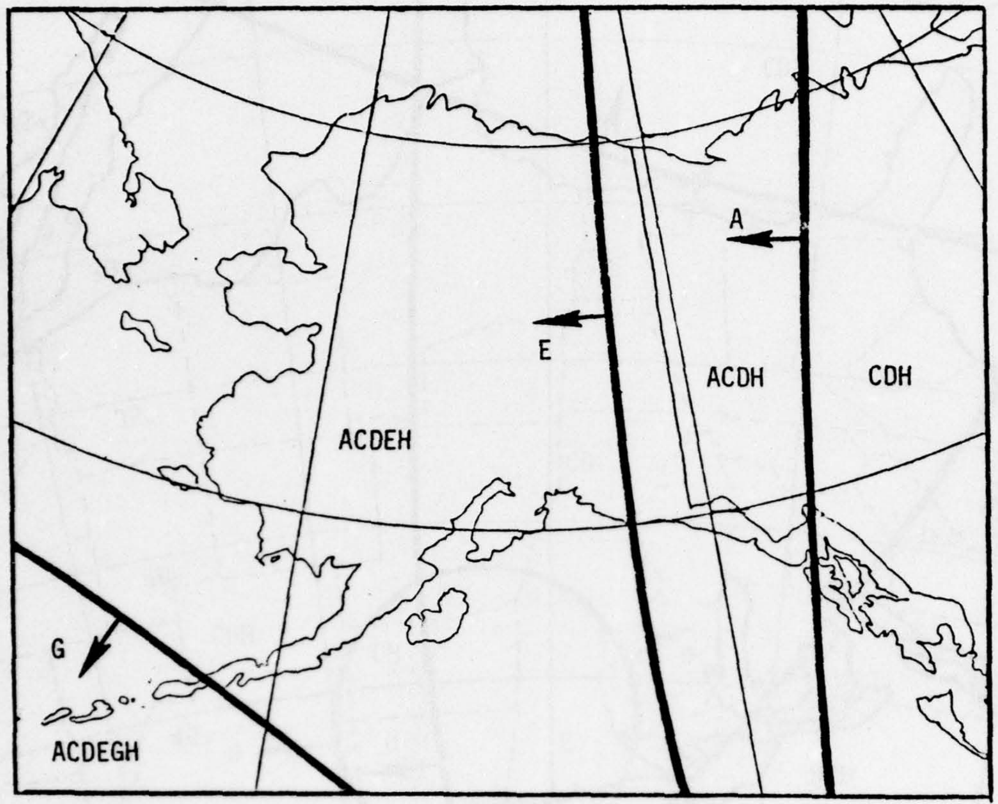


Figure 5 Omega Coverage Prediction for Alaska and Alaska Offshore at Noon Midsummer

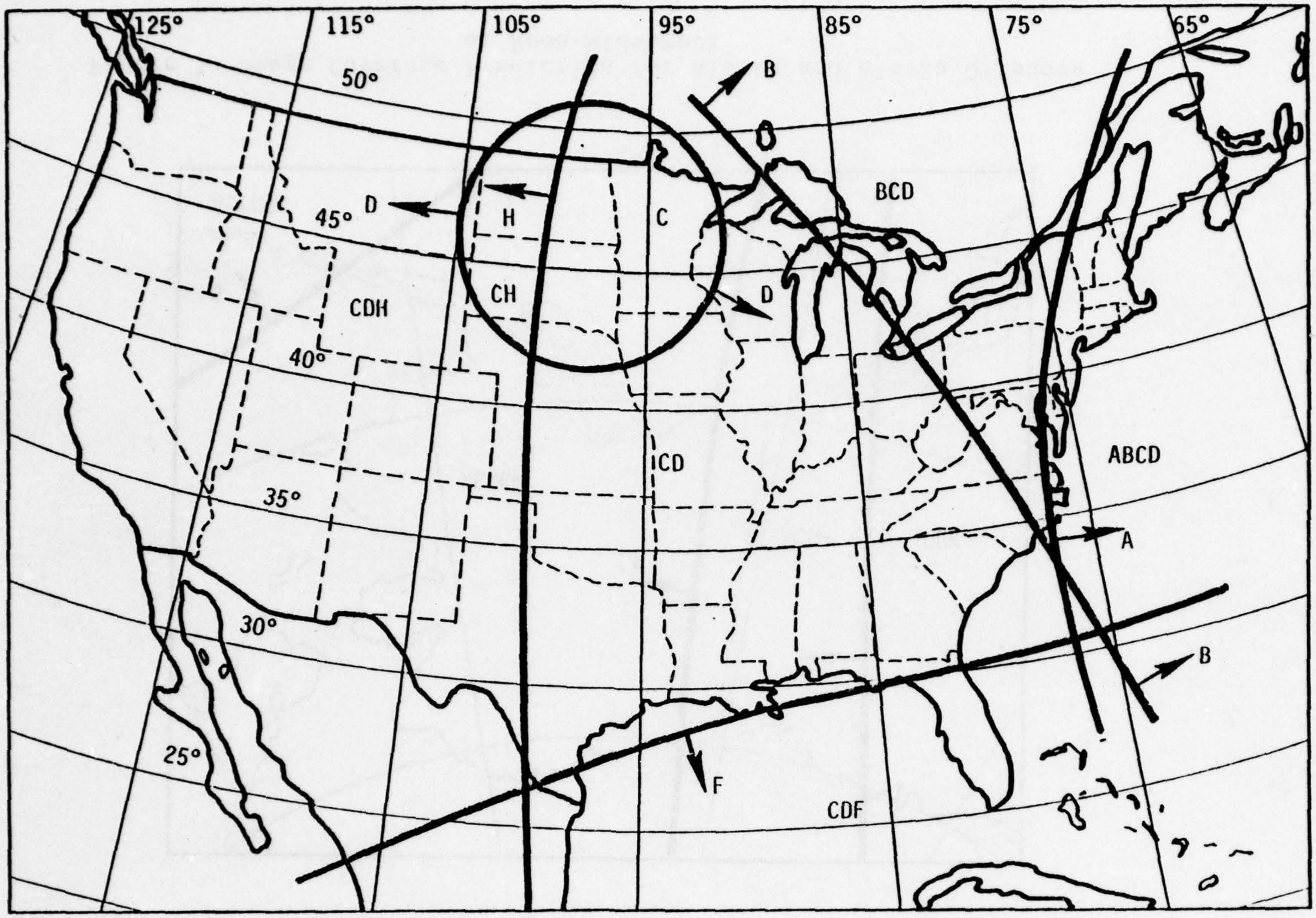


Figure 6 Omega Coverage Prediction for CONUS and CONUS Off-shore at Noon Midsummer

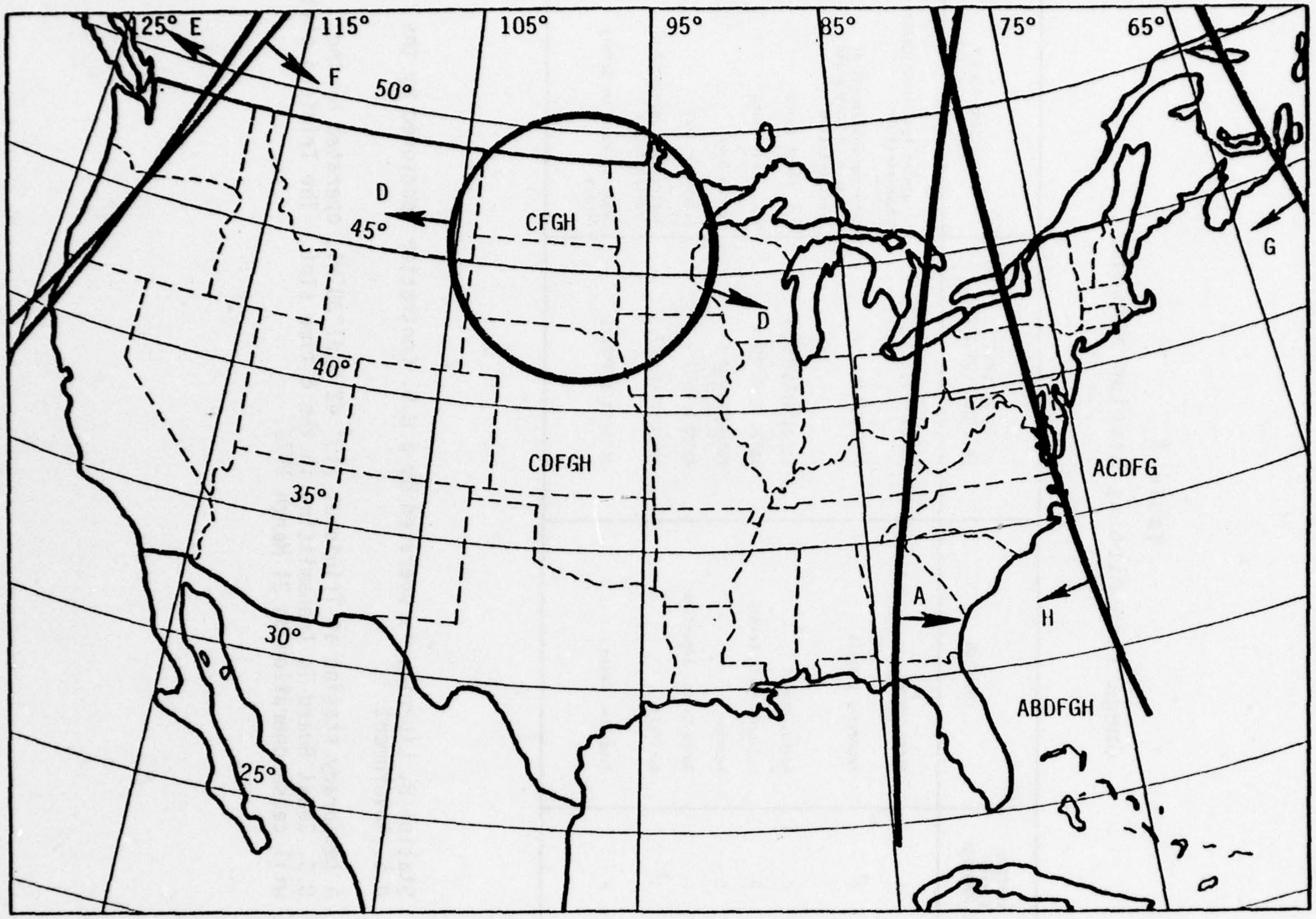


Figure 7 Omega Coverage Prediction for CONUS and CONUS Off-shore at Midnight Midwinter

Table 3

Omega Transmitting Station Network

STATION LETTER DESIGNATION	LOCATION	APPROXIMATE LATITUDE/LONGITUDE	COGNIZANT AGENCY
A	Aldra, Norway	66°25'N/13°08'E	Norwegian Telecommunications Administration
B[1]	Monrovia, Liberia	6°18'N/10°40'W	Liberian Department of Commerce, Indusdry and Transportation
C	Haiku, Hawaii	21°24'N/157°50'W	U.S. Coast Guard
D	LaMoure, North Dakota	46°22'N/98°20'W	U.S. Coast Guard
E	Reunion	20°58'S/55°17'E	French Navy
F	Golfo Nuevo, Argentina	43°03'S/65°11'W	Argentine Navy
G[2]	Australia	38°29'S/146°56'E	Australian Department of Transportation
H	Tsushima, Japan	34°37'N/129°27'E	Japanese Maritime Safety Agency

1. Station B, Liberia, is operated by a U.S. Contractor sponsored by the U.S. Government

2. A temporary station at Trinidad, (10° 42'N/61°38'W), operated by the U.S. Coast Guard is transmitting in the G time slot. The Trinidad station will cease operation on 31 March 1978.

ONSOD oversees U.S. interests in Omega, operates two permanent stations and is conducting a signal monitoring and data update program. As part of their monitoring program, ONSOD issues a weekly status report on Omega system operation. The report is available to users by mail or TWX. An abbreviated version is also available on a recorded message via the telephone. ONSOD is also operating the temporary station at Trinidad which is scheduled to go off the air on 31 March 1978. There is speculation that this station will remain on the air until the eighth permanent station becomes operational. In addition, ONSOD provides technical support to the bilateral agreement process for the establishment and operation of stations by host nations.

Seven of the eight stations are currently operating on a permanent basis. Negotiations are continuing with Australia for the establishment and operation of the eighth permanent station which is expected to be on the air by 1980.

The accuracy of Omega is nominally 1-2 nm (RMS). This is based on useable signals from three ore more stations, the use of predicted phase corrections, (PPCs), and reasonably good line-of-position (LOP) crossing angles. The LOP geometry over the Alaska and Alaska Offshore area is excellent as illustrated in Figure 8 providing further support to the viability of Omega for that region. The crossing angles of the principal LOPs over CONUS are noteably less favorable as illustrated in Figure 9.

The propagation corrections (PPCs) needed to compensate for the diurnal phase shifts caused by the diurnal variations in the ionosphere are fairly well understood and are being continually improved as more data becomes available. However, there are two other effects which may require more attention. One is modal interference which could preclude the use of signals from a given station at night over certain signal paths, particularly in the westerly direction from the station. The other

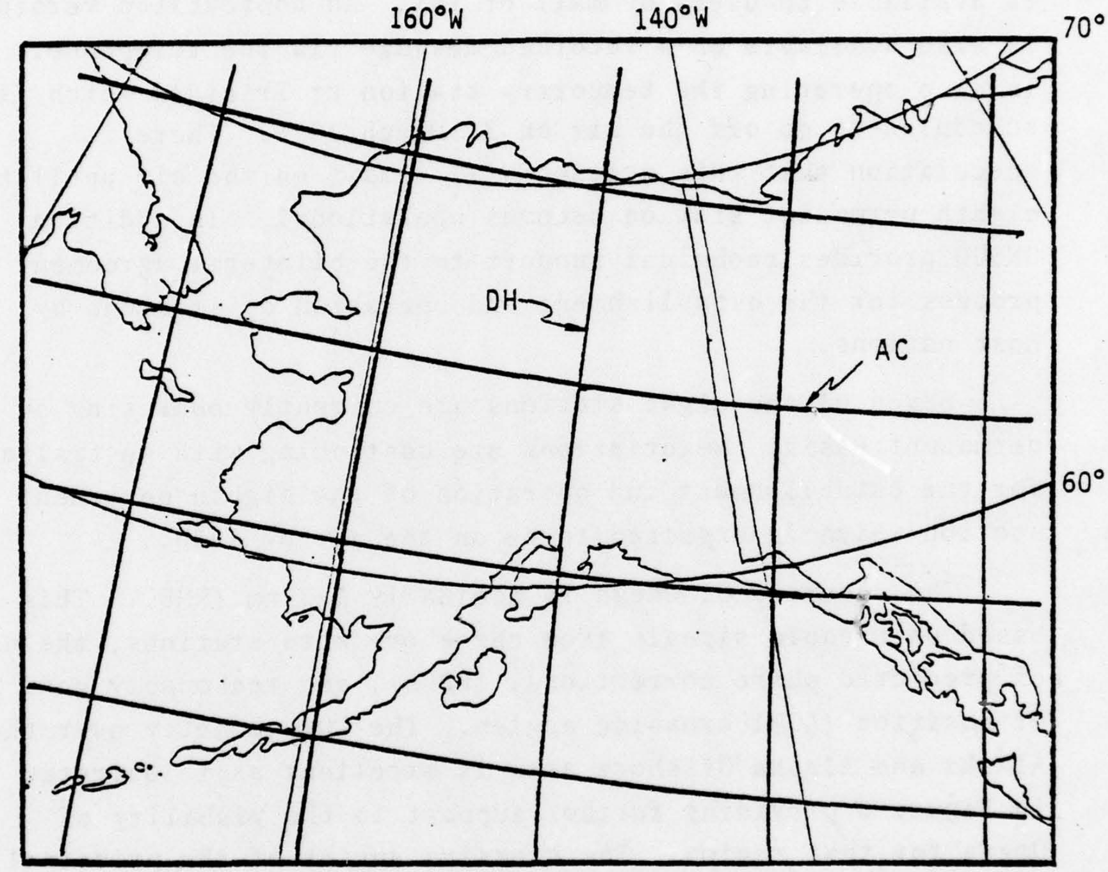
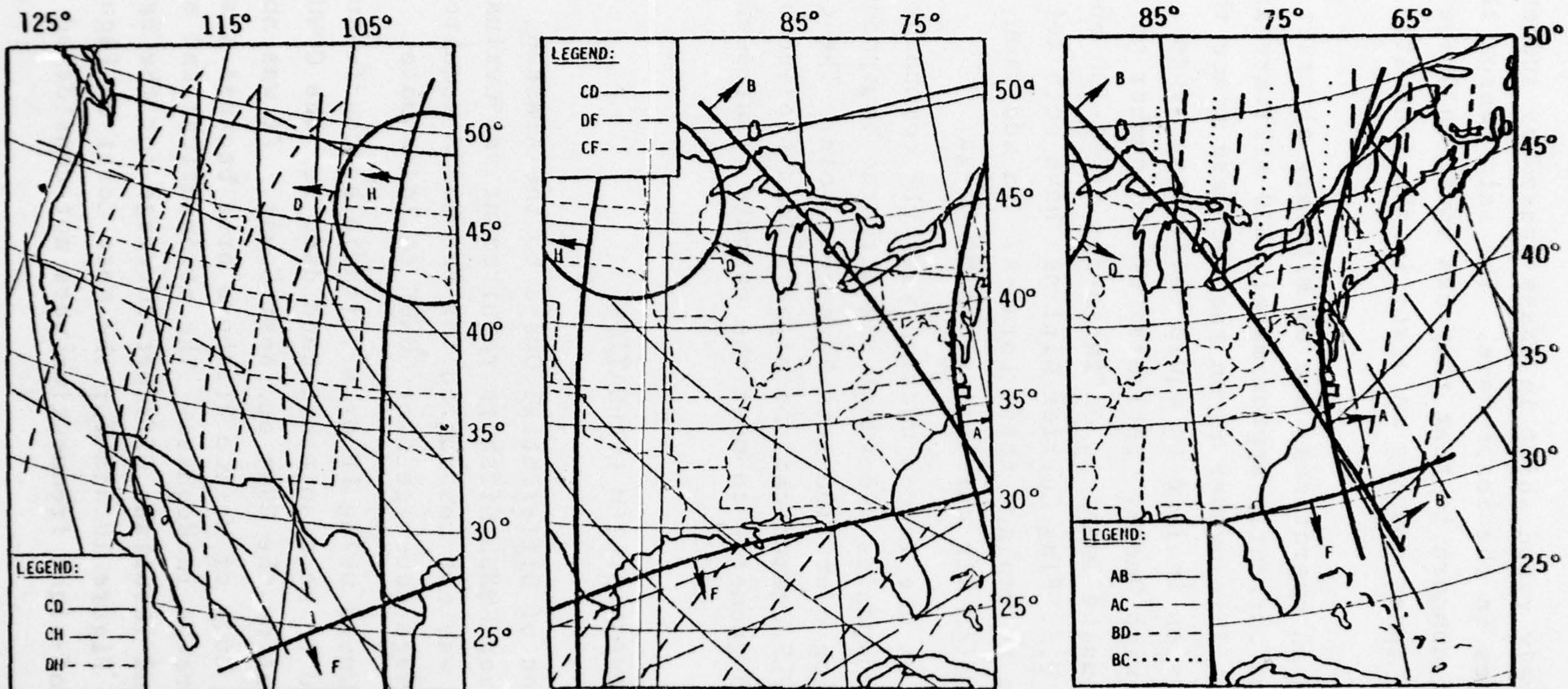


Figure 8 A-C and D-H LOP's in Alaska



a) Western CONUS

b) Central CONUS and Gulf of Mexico Offshore

c) CONUS East Coast Off-shore and Great Lakes area

Figure 9 CONUS Omega LOP's for Noon Midsummer

effect is a relatively rapid shift in phase caused by sudden unpredictable changes in the ionosphere. The main reason these pertubations are of concern is that they can cause an Omega receiver to slip one or more lanes causing an error in the indicated position.

Omega has been in operational use on military aircraft since about 1970 and currently approximately 300 military aircraft are Omega equipped. This number is on the increase since the U.S. Air Force decision in 1976 to equip their long range transport aircraft with Omega. Estimates of the number of civil aircraft currently using Omega is on the order of 50-100 but on the increase. Two U.S. Flag Carrier Airlines have both let contracts for Omega to replace their Loran-A. In addition, there are a number of foreign air carriers ordering Omega.

Omega is also in use in conjunction with VLF communications signals. Two U.S. companies are supplying airborne equipment of this type of which over 1100 sets have been sold. The combined use of Omega with VLF communications signals does provide adequate signal coverage and geometry to meet the enroute requirements over CONUS.

2.5 DIFFERENTIAL OMEGA SYSTEM EVALUATION

The application of Differential Omega to the Alaskan, Alaskan Offshore, and CONUS Offshore requirement was evaluated. Differential Omega was not considered for the CONUS requirement because standard Omega coverage over CONUS is inadequate.

Differential Omega using LF or MF, (radio beacon frequency channels) was found to be a suitable candidate for the CONUS Offshore requirement on the East and West Coast. It was not considered for the Gulf of Mexico Offshore area because standard Omega coverage there is inadequate. The aeronautical and maritime beacon locations and resultant Offshore coverage for the East Coast are shown on Figure 10 and for the West Coast on Figure 11. VHF or other line-of-sight frequencies were not considered for

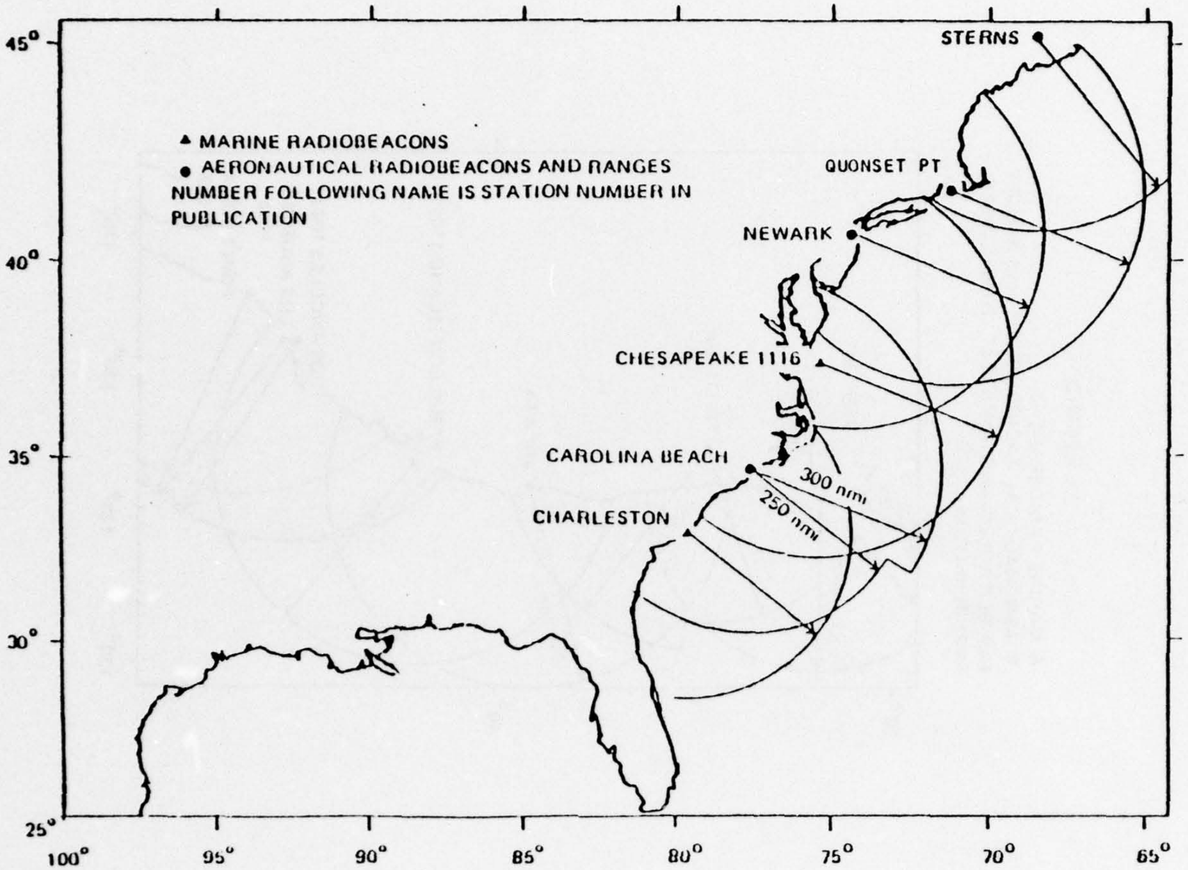


Figure 10 Differential Omega LF Stations for East Coast Offshore Region

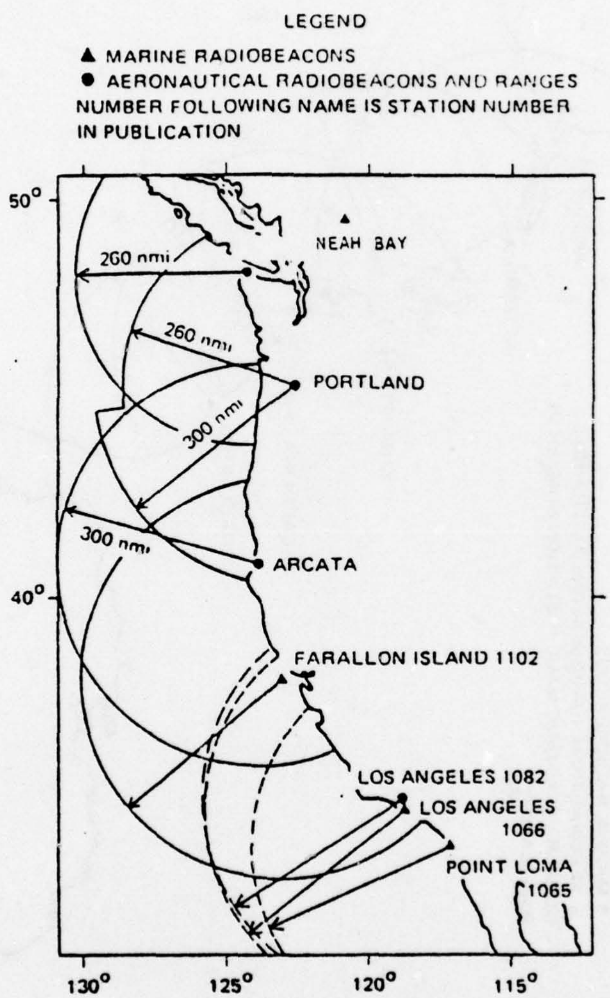


Figure 11 Differential Omega LF Stations for West Coast Offshore Region

the telemetry data link for Offshore because the line-of-sight range does not meet the coverage requirement. Since Loran-C has been approved for the CCZ maritime requirement and most of the stations are already implemented with the remainder to be completed by 1980, it is not likely that Differential Omega will be necessary or desirable for this requirement area.

For the Alaska and Alaska Offshore areas, Differential Omega was found to be a viable candidate for consideration. This is based on the excellent standard Omega coverage over the area. Standard Omega meets the enroute and low density terminal area requirements. The addition of Differential Omega will meet the non-precision approach requirements as well as provide greater accuracy throughout the Differential Omega coverage area. Eighteen (18) Differential Omega stations, based on using LF-HF (radio beacon) frequency channels), are required for total coverage over the Alaska and Alska Offshore areas. The Differential Omega station locations and coverage are shown on Figure 12. VHF and other line-of-sight frequencies for the telemetry data link are not considered viable because of the mountainous terrain and the Offshore range requirement.

Differential Omega is a system concept, which has been evaluated, for reducing the position errors of standard Omega. Figure 13 shows the operational concept of Differential Omega. The ground unit consists of a monitor receiver at a fixed, known location, and an uplink transmitter. The monitor receiver measures the actual Omega signal phases, and compares them with the nominal phase characteristics for the known monitor location. The differences between the actual and nominal phase measurements are used to generate correction data, which are uplinked to Differential Omega users in the service area. The Differential Omega receiver decodes the correction data from the uplink and uses these to correct the Omega signals measured by the user Omega equipment. For reasonable ranges, less than 200 nm, there exists good correlation between the Omega signal errors measured by the monitor station

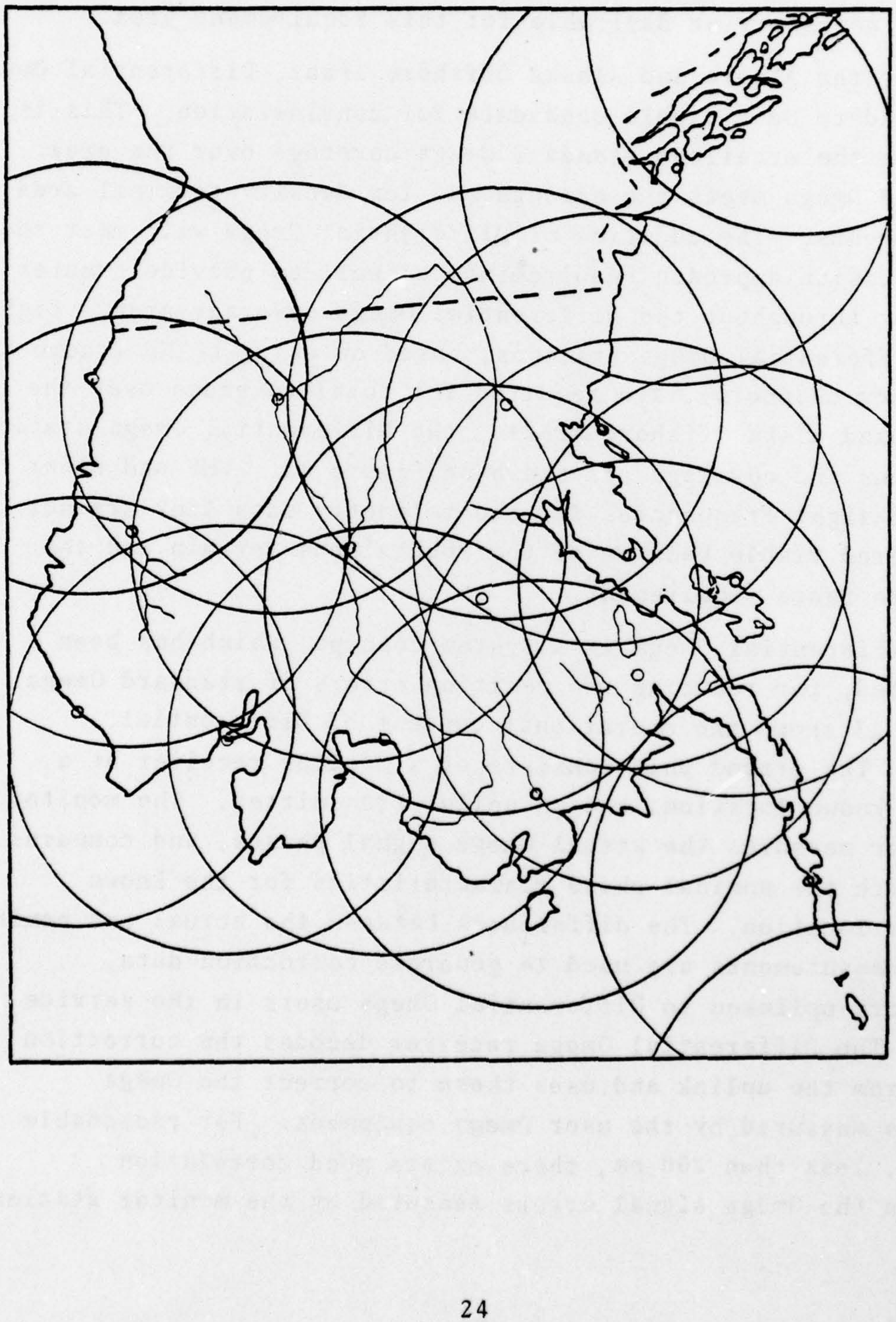


Figure 12 Alaska and Alaska Offshore Differential Omega Stations (300 nmi Radius)

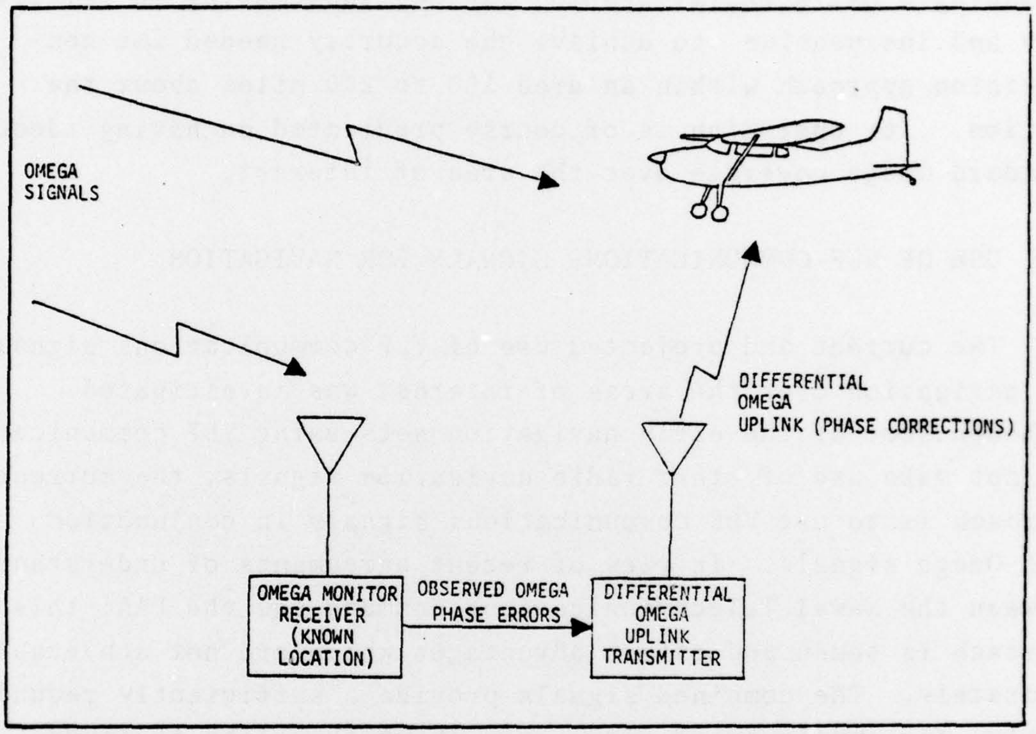


Figure 13 Differential Omega Concept

and by the user equipment, hence, Differential Omega can provide substantial accuracy enhancement. This accuracy enhancement is based on having reasonably good standard Omega coverage over the area of interest. Differential Omega can reduce the errors resulting from propagation phase prediction errors, but cannot correct for poor phase measurements (due to poor S/N ratios) or poor Omega station/receiver geometry.

Demonstration tests have shown the accuracy of Differential Omega to range from 0.25 nmi to 1.0 nmi RMS depending on distance from the Differential station.

The primary advantage of Differential Omega is that the cost of adding a Differential station is low, thus making it relatively easy and inexpensive to achieve the accuracy needed for non-precision approach within an area 150 to 200 miles about the station. Its operation is of course predicated on having adequate standard Omega coverage over the area of interest.

2.6 USE OF VLF COMMUNICATIONS SIGNALS FOR NAVIGATION

The current and projected use of VLF communications signals for navigation over the areas of interest was investigated. Although some of the early navigation sets using VLF communications did not make use of other radio navigation signals, the current approach is to use VLF communications signals in conjunction with Omega signals. In view of recent agreements of understanding between the Naval Telecommunications Command the the FAA, this approach is sound and offers advantages which are not achievable separately. The combined signals provide a sufficiently redundant, stable, and synchronized radio grid about the globe to assure adequate useable signals anywhere at any time. The redundancy is particularly important because of the down times of individual stations for scheduled and unscheduled maintenance.

Based on geometry and signal-to-noise ratios, there should be at least four VLF communication stations providing usable signals at any location and time over the CONUS, Alaska, and Offshore areas which supplemented with Omega signals will provide adequate redundancy and useable geometry.

The VLF Communication System operated by the U.S. Navy provides a global, all weather, highly redundant communications service to ships and submarines. There are ten stations available with assigned frequencies between 16 kHz and 24 kHz. Table 4

Table 4
VLF Communications Stations

IDENT.	LOCATION	FREQUENCY kHz
NSS	Annapolis, Maryland	21.4
NAA	Cutler, Main	17.8
NBA	Balboa, Panama Canal Zone	24.0
NLK	Jim Creek, Washington	18.6
NPM	Lualualei, Hawaii	23.4
NWC	Northwest Cape, Australia	22.3
GBR	Rugby, England	16.0
NDT	Yosami, Japan	17.4
JXN	Helgeland, Norway	16.4
GQD	Anthorne, England	19.0

lists their identification, location, and frequency. High power is radiated, ranging from 100 KW to 1000 KW, to assure high signal to noise ratios at any receiver location. Stable signals are propagated over long distances as a result of the spherical earth-ionosphere waveguide phenomena similar to that experienced at the lower VLF frequencies of Omega. However, because of the higher frequencies, the incidence of modal interference is higher. Consequently, there are variations in the propagation velocity and attenuation caused by changes in the height and density of the ionosphere similar to that observed at the Omega frequencies. However, these variations do not present a particularly severe problem in terms of accomplishing the communications mission because of the highly redundant nature of the communications system. Also, for communications it is only necessary to track and detect changes in frequency and not phase.

Because of the use of the VLF communications signals for frequency and time reference in addition to the vital communications mission, there has been a continuing effort to improve the stability of the transmitted signals. By the application of multiple cesium beam standards for precise frequency and phase control at each station, and the synchronization of all stations to a Universal Coordinated Time (UTC), a highly repeatable phase stable VLF radio covering the globe was achieved. This occurred around 1970, at which time the Omega system was semi-operational with four temporary stations. The potential application of the VLF Communication phase stable grid to navigation was recognized and a U.S. company developed an airborne navigation system based on the use of these signals. The first flight testing of the developmental set began in 1970. The sets were designed to track the phase of the carrier frequency of three or four VLF Communication stations which provided two lines-of-position (LOPs) in the radio grid network. Generally, the RF section was designed to receive eight signals, Often including Omega unique frequencies, so that the user could select the best set of three or four stations for his intended route. With the FSK signal format, the carrier duty cycle on the

average is 50%, which with the high transmitted power provides a high average signal-to-noise ratio, making phase tracking relatively easy. Note that commutation is not necessary as in Omega since each station is identified by its unique frequency. The relatively easy phase tracking of the VLF Communication signals is being somewhat complicated by a change in signal format to minimum shift keying (MSK). Transition to MSL began in 1976, and all stations are expected to be modified for MSK by the end of 1978.

With the MSK format the carrier frequency is not transmitted and thus cannot be tracked. There are several ways to recover the apparent carrier phase. One technique is to recover the message bit format. A simpler technique is to double either side tone frequency and track the resultant phase. Since doubling adds noise, this technique requires signal-to-noise ratios greater than unity which will usually be the case for the high power VLF Communication stations. Manufacturers of navigation avionics using VLF Communication signals have developed and implemented means of accomodating the MSK format.

The first flight testing of a feasibility model of an airborne navigation system based on the use of VLF communications signals began in 1970. Since that time, over 1200 aircraft have been equipped with navigation sets based on VLF communications signals. The sets are produced by several U.S. companies. Prices range from \$16,000 to \$50,000. Application was generally found by those users operating in areas not serviced by any other radio-based navigation aid. More recently (1976-77), at least two manufacturers of Omega sets began offering an option to include the use of VLF Comm signals to augment Omega.

In 1975, the FAA requested the U.S. Navy to assume a navigational mission repsonsibility for the Navy VLF stations. The request was denied. Since that time, a better understanding of the use of the VLF signals for navigation has been achieved

by both parties. In September 1976, the Navy informed the FAA that there is no objection to the use of VLF Comm for navigation provided that the stations are not assigned additional missions as NAVAIDS, and notification procedures of the U.S. Naval Observatory are satisfactory to all concerned. In addition, the FAA sponsored an FAA/DoD/Industry meeting on 14 September 1976 to discuss the use of VLF Comm for navigation purposes. A preliminary proposed Omega/VLF Approval Requirement was issued and critiqued at that meeting. A revised version of the Approval Requirement was issued as a NOTAM and an Advisory Circular is in preparation. In May 1976, the FAA Western Region certified a VLF/Omega set as primary means of navigation (but not sole means) for ENROUTE navigation per A.C. 90-45A within the 48 continguous United States and the District of Columbia.

2.7 NON-PRECISION APPROACH ANALYSIS SUMMARY

A potentially significant benefit offered by the candidate systems considered is the support of non-precision approach (NPA) requirements. This derives from the wide area and essentially all altitude coverage characteristics of the systems. The characteristics of the systems considered are much the same in regard to servicing non-precision approaches. For these reasons, a separate element of the study, which analyzed all systems considered, was devoted to this topic.

It was found that Loran-C exceeded the NPA requirements for the CONUS, Alaska, and Off-shore regions. Differential Omega could also meet the NPA requirements given that standard Omega coverage is available in the area of interest. Therefore, Differential Omega could support NPA requirements in Alaska, Alaska Off-shore, East Coast CONUS Off-shore, West Coast Off-shore, but not CONUS mid-continent or Gulf of Mexico Off-shore. Standard Omega cannot support NPA requirements because of inadequate accuracy. VLF Comm by itself cannot be considered a candidate

for NPA because the stations are not dedicated to navigation and are subject to unannounced signal interruptions.

Of the 238 airports analyzed in CONUS mountainous areas, it was found that the ceiling minima could be reduced at 123 airports and could be reduced by more than 50 feet at approximately 80 airports (Figure 14). For the rest of the airports, terrain is not a major factor, hence, on the average the published minima are lower than for the mountainous region. Figure 15 shows a histogram of the ceiling minima of the 1303 airports analyzed in the non-mountainous region of CONUS. Ceiling reductions on the order of 50 feet are achievable at a number of airports through approach procedure modifications such as elimination of the requirement forcircling approaches or implementation of a final approach fix.

Forty-four airports were analyzed in Alaska. Of these, reductions in ceiling minima were achievable at 21. A histogram of the minima reductions in Alaska are shown in Figure 16.

Additional benefits that were found are derived from the inherent area navigation capability and availability of extended coverage from the candidate systems. The area navigation capability provides for simplification of the approach procedures, from that of using circling approaches and procedure turns to using simple straight-in approaches. Also, missed approach and curved approach guidance are available for obstruction avoidance. The extended coverage provides non-precision approach service at airports currently not receiving this service.

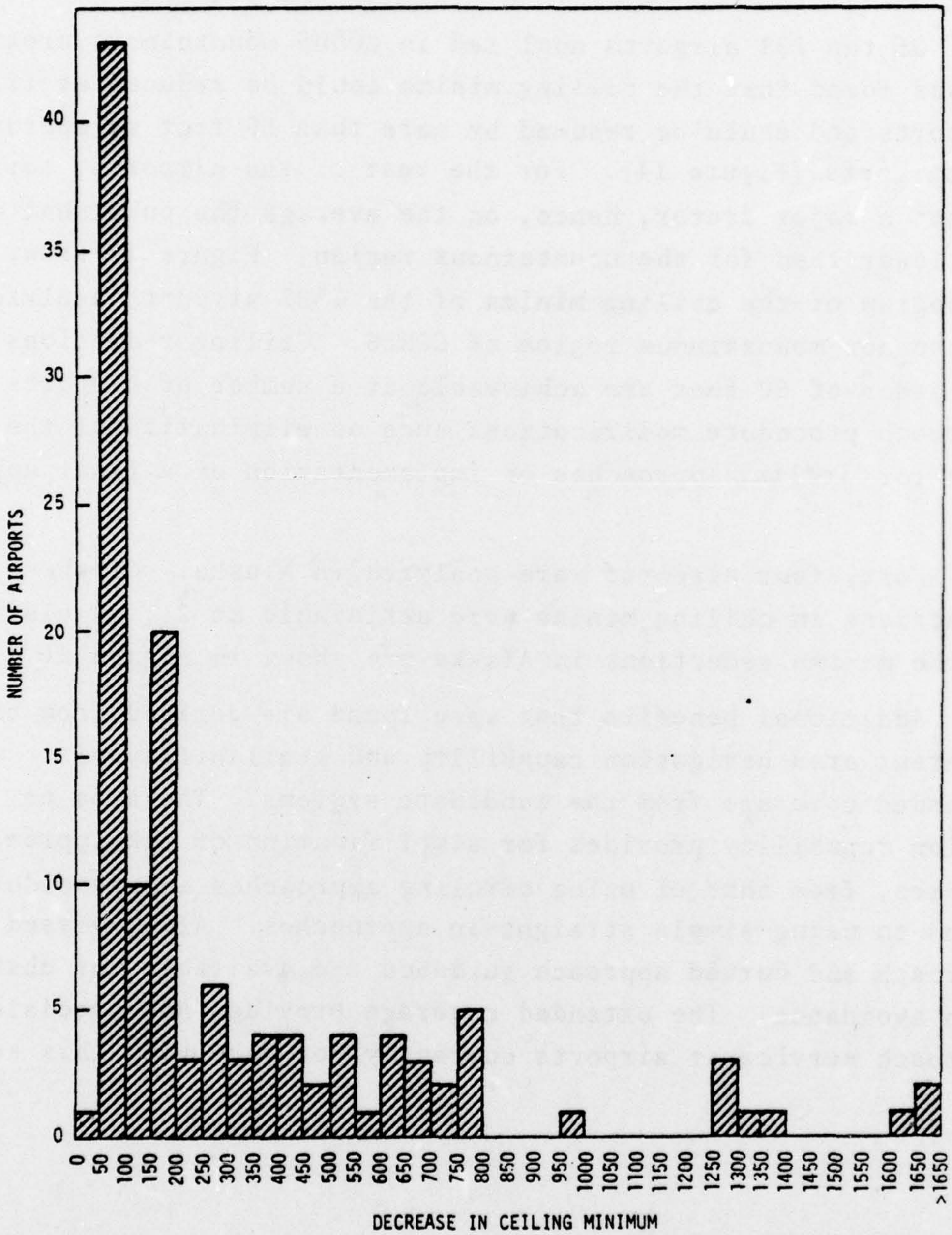


Figure 14 Histogram of Ceiling Minima Reduction for Aircraft Category A

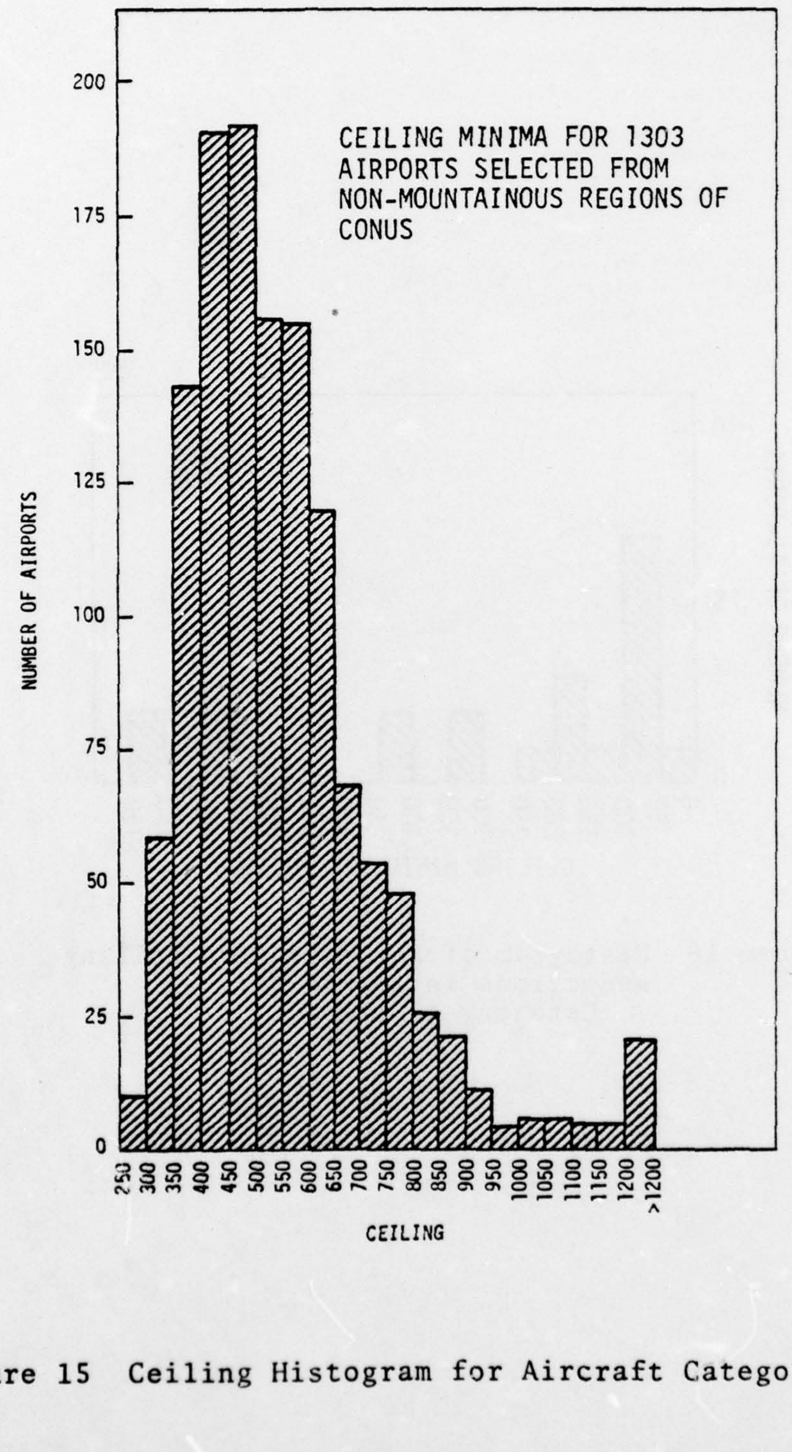


Figure 15 Ceiling Histogram for Aircraft Category A

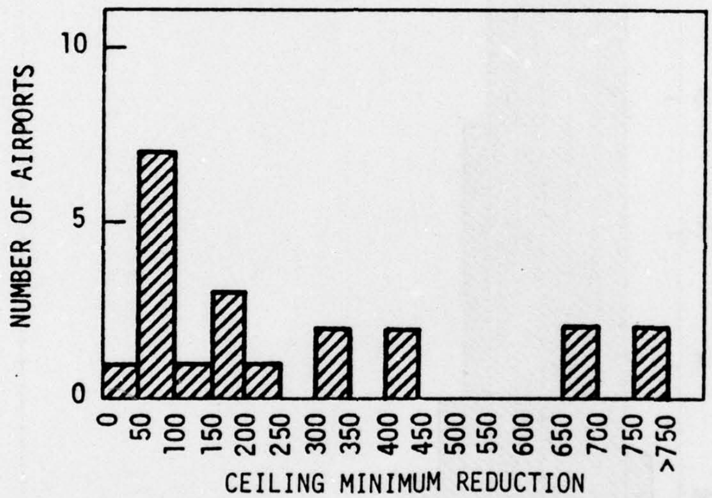


Figure 16 Histogram of Estimated NPA Ceiling Reductions in Alaska for Category A Aircraft

2.8 SUMMARY CONCLUSIONS

Based on the approved CCZ Loran-C configuration, coverage for Offshore and Alaska is complete except for the North Slope of Alaska area. One additional station would be required to complete the Alaska coverage. Given the additional three stations proposed for CONUS midcontinent, primary CONUS coverage would be complete. However, additional stations would be required for civil aviation use to meet redundancy requirements in all three areas. Estimates to meet the redundancy requirements for all three areas range from 19 to 23 more stations.

The demonstrated accuracy of Loran-C is 0.25 to 1.0 nm (RMS) absolute, and 300 feet (RMS) in repeatability. These accuracies are more than adequate to meet the requirement of all phases of civil aviation requirements under consideration.

Omega was found to be an excellent candidate for Alaska and Alaska Offshore with good coverage from four to six of the eight stations, depending on time of year and day. Based on coverage, signal-to-noise ratios, and geometry, Omega can meet the enroute and low density terminal area requirements over the entire Alaska and Alaska Offshore region.

The final Omega system cannot be considered a candidate for CONUS. During midsummer and midday, a large part of the central CONUS will receive usable signals from only two stations with a region about the North Dakota station limited to only one station. Recent test data indicate that the coverage boundary for station F (Argentina) may not actually reach as far north as analytical predictions would indicate. This means that the Offshore area in the Gulf of Mexico may not be covered by more than two stations for much of the time.

The accuracy of Omega is nominally 1-2 nm (RMS). This is based on usable signals from three or more stations, the use of propagation corrections (PPCs), and reasonably good line-of-position (LOP) crossing angles. The LOP geometry over the

Alaska and Alaska Offshore area is excellent for providing further support to the viability of Omega for that region. The crossing angles of the principal LOPs over CONUS are notably less favorable.

Differential Omega using LF or MF (radio beacon frequency channels) was found to be a suitable candidate for the CONUS Offshore requirement on the East and West Coast. It was not considered for the Gulf of Mexico Offshore area because standard Omega coverage there is inadequate. VHF or other line-of-sight frequencies were not considered for the telemetry data link for Offshore because the line-of-sight range does not meet the coverage requirement. Since Loran-C has been approved for the CCZ maritime requirement and most of the stations are already implemented with the remainder to be completed by 1980, it is not likely that Differential Omega will be necessary or desirable for this requirement area.

For the Alaska and Alaska Offshore areas, Differential Omega was found to be a viable candidate for consideration. This is based on the excellent standard Omega coverage over the area. Standard Omega meets the enroute and low density terminal area requirements. The addition of Differential Omega will meet the non-precision approach requirements as well as provide greater accuracy throughout the Differential Omega coverage area. Eighteen (18) Differential Omega stations, based on using LF-HF (radio beacon frequency channels), are required for total coverage over the Alaska and Alaska Offshore areas. VHF and other line-of-sight frequencies for the telemetry data link are not considered viable because of the mountainous terrain and the Offshore range requirement.

Although some of the early navigation sets using VLF communications did not make use of other radio navigation signals, the current approach is to use VLF communications signals in conjunction with Omega signals. In view of recent agreements of understanding between the Naval Telecommunications Command and the FAA,

this approach is sound and offers advantages which are not achieveable separately. The combined signals provide a sufficiently redundant, stable, and synchronized radio grid about the globe to assure adequate usable signals anywhere at any time. The redundancy is particularly important because of the down times of individual stations for scheduled and unscheduled maintenance.

Based on geometry and signal-to-noise ratios, there should be at least four VLF communication stations providing usable signals at any location and time over the CONUS, Alaska, and Offshore areas which, supplemented with Omega signals, will provide adequate redundancy and usable geometry.

A potentially significant benefit offered by the candidate systems considered is the support of non-precision approach (NPA) requirements. This derives from the wide area and essentially all-altitude coverage characteristics of the systems. The characteristics of the systems considered are much the same in regard to servicing non-precision approaches. For these reasons, a separate element of the study, which analyzed all systems considered, was devoted to this topic.

It was found based on study results that Loran-C exceeded the NPA requirements for the CONUS, Alaska, and Offshore regions. Flight test and other evaluation studies will be required to substantiate these results. Differential Omega could also meet the NPA requirements given that standard Omega coverage is available in the area of interest. Therefore, Differential Omega could support NPA requirements in Alaska, Alaska Offshore, East Coast CONUS Offshore, West Coast Offshore, but not CONUS midcontinent or Gulf of Mexico Offshore. Standard Omega cannot support NPA requirements because of inadequate accuracy. VLF Comm by itself cannot be considered a candidate for NPA because the stations are not dedicated to navigation and are subject to unannounced signal interruptions.

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